Design Characteristics of Electromagnets for Telephone Relays

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NOTE: The electromagnets described are confined to relays, although the principles involved apply as well to selector magnets, clutch magnets and electromagnets in general. A treatment from the viewpoint of the telephone engineer is given of the important considerations which determine the design of the magnetic parts of relays and the economics of the winding dimensions. A knowledge of these factors as well as of the general considerations which are discussed is of great importance in the selection and application of relays to the telephone system. The operating and economic importance to the Bell System of the great number of relays required in the operation of the plant has been described in a previous paper.[1]

INTRODUCTION

ELECTROMAGNETS or relays as generally used in telephone switchboards are simply switches which are controlled electromagnetically. These switches may be required to open or close a number of separate and distinct circuits simultaneously or in a certain sequence. In many cases it is essential that the relay switch be opened or closed very quickly as this time may have a direct influence on the amount of apparatus required and consequently the first cost of the plant. The operating time of the relays also has a direct influence on the time required to establish a telephone connection. The above statements are particularly evident in automatic systems where selector apparatus is required to establish a connection between parties but is released during the conversation. It follows that the number of selector circuits and relays therein depends upon the amount of traffic and time required for the selectors to establish the connection.

To establish a telephone connection between two parties in certain automatic telephone systems, requires the opening and closing of about 2,000 electric switches of which 1,200 are operated by simpler types of electromagnetic relays. In a typical manually operated system a call is completed by the opening and closing of about 112 switches of which 70 are operated by relays. It is therefore evident that the relay switches must operate both quickly and reliably and maintain a high degree of stability throughout a long period of service.

In controlling the various circuits in telephone systems by relays, the character of the circuits determines the construction of the relay switches. If large currents are to be controlled the relay switch

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[1] Relays in the Bell System, S. P. Shackleton and H. W. Purcell, *Bell System Tech. Journ.*, Vol. 3, p. 1, 1924.

construction differs materially in ruggedness from the construction where relatively small currents are to be controlled. In the operation of the relays larger amounts of power, of course, are required for those having the more rugged construction. It is also evident that more power is required for fast operation than for comparatively slow operation. Fast operation of relays is also dependent upon circuit arrangements which are effective in lowering the electrical "time constant" of the circuits in which the relays operate.

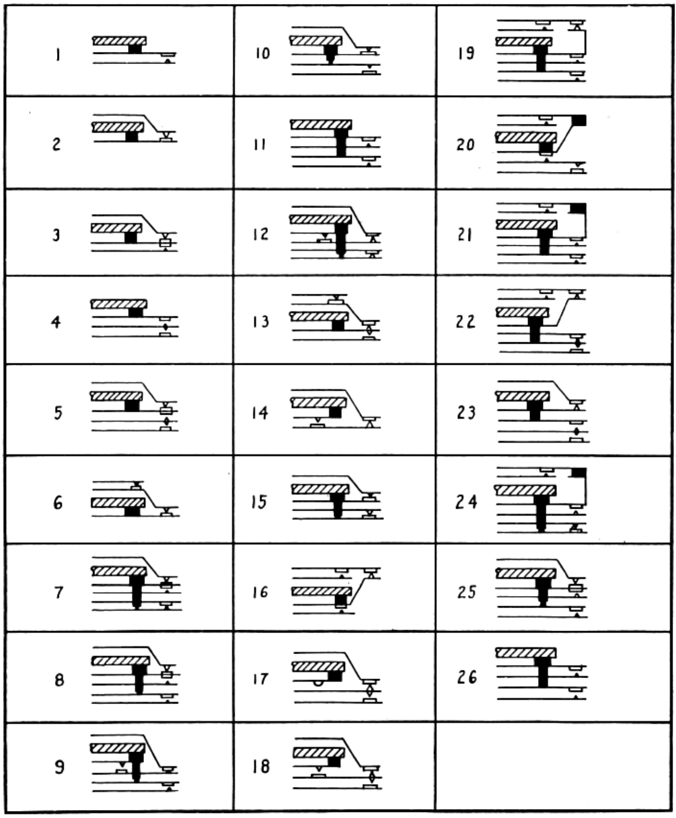

Fig. 1—Spring Combinations—Flat Type Relay

Electromagnets in telephone systems are designed and used for a great variety of conditions. The more common uses are for relay operation on direct current battery of 20 to 28 volts or 40 to 45 volts. Such relays perform a great number of switching functions, a few of which are shown in Figs. 1 and 12. Other designs are used for operation on alternating currents, ranging from 16 cycles ringing frequency to voice frequencies of 2,000 cycles per second. The load or work required of these relays and electromagnets varies from a fraction of a gram controlled through a few thousandths of an inch to 25 pounds controlled through a distance of ¼ of an inch. Some relays are operated where the annual power charges are negligible while in other designs annual power charges may be controlling. The technical considerations which determine the design features, therefore vary throughout a wide range as to the proportioning of the magnetic parts and the design of the windings. Other general design characteristics that must be carefully considered are as follows:

1. Operating capability of the structure—
    - (a) Switching conditions or circuit control required of the relay.
    - (b) Design of contacts required to safely carry the energy required by condition (a) throughout the estimated "life" requirements of the switchboard.
    - (c) Capability of the structure with respect to the input power to satisfy condition (a).
2. Determination of winding best suited for the circuit.
3. Temperature limitation of the winding under extreme conditions.
4. Ease of adjustment.
5. Permanence of adjustment—
    - (a) For a period of service operations representing the "life" of the relay in the switchboard.
    - (b) Under extreme weather conditions.
6. Size and mounting facilities.
    - (a) When used for additions to old equipment where it should mount in the same space as the apparatus it replaces.
    - (b) Economy of space for new equipments.
    - (c) Stability of mounting.
7. Terminals—arrangement and distribution for most advantageous electrical connections.
8. Insulating materials.
    - (a) Windings.
    - (b) Switch control of contacts.
9. Cover design.
    - (a) Protection from dust.
    - (b) Effect of cover on operation and protection from stray flux.
10. Speed of operation and release.
11. Transmission efficiency with respect to voice frequencies.

12. Mechanical design features with special reference to manufacture.

13. Electro-mechanical efficiency.

14. First cost and annual charges.

As it is not within the scope of the present paper to discuss in detail all of the above characteristics the following have been selected as perhaps the more important and the most interesting:

1. The design of the magnetic parts for various telephone switchboard requirements.

2. Methods of calculating windings and the determination of temperature characteristics.

3. Considerations which determine the spool dimensions.

4. Discussion of designs used extensively in the telephone plant.

Design of Magnetic Parts

The fundamental requirements of an electromagnet or relay are generally the load or pull, the distance through which the load must be moved and the time limits of operation. The last requirement, of course, is reflected in the load or pull requirement as an added pull or force of acceleration.

The fundamental constants of design are the flux leakage coefficient, the core flux density and the flux density in the pole face or area where the pull is exerted. If the designer is given data which fix these constants the remainder of the work is usually a comparatively simple matter of calculation.

The leakage coefficient has been determined experimentally throughout a range of designs where the load to be controlled varied from 1 gram to 5,000 grams. The results show that the leakage depends almost entirely upon the armature air-gap reluctance and the ratio of the core length to the core diameter. The leakage flux is defined as that percentage of the total core flux which does not cross the armature air-gap, and consequently can not be utilized for producing traction. The per cent useful flux is then the ratio of the flux crossing the armature air-gap to the total flux in the relay core. The curves in Fig. 2 for single spool electromagnets and Fig. 3 for double spool electromagnets give the per cent useful flux for various air-gaps and core lengths which are expressed in terms of the core diameter. In cases where the core is round and the pole face area is equal to the core section these data may be used directly. If, however, the pole face area differs from the core section, the air-gap used in looking up the leakage in Fig. 2 and Fig. 3 should be reduced to a value which, with a pole face area equal to the core section, would give the same air-gap reluctance.

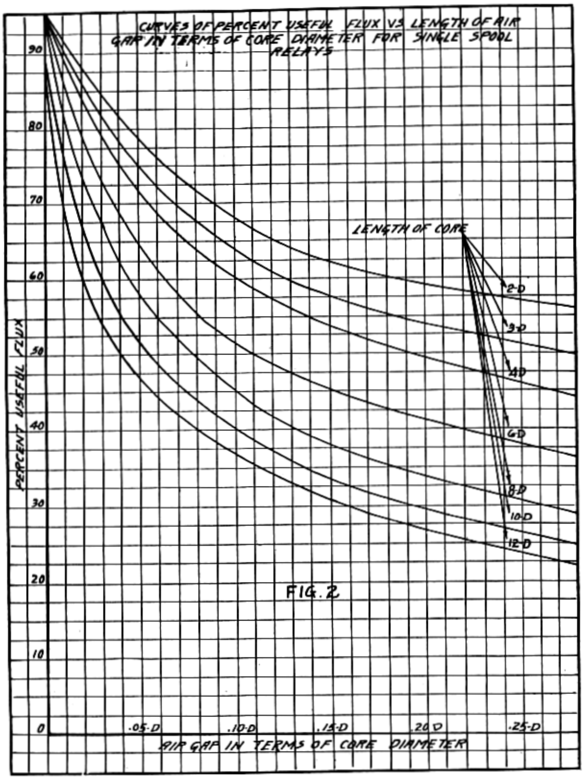

Fig. 2—Curves of Percentage Useful Flux vs. Length of Air Gap in Terms of Core Diameter for Single Spool Relays

The core flux density and the pole face density depend largely upon the requirements of the particular design, but the considerations outlined in the next four paragraphs are of prime importance.

In some cases the annual power charges are relatively unimportant, there being plenty of power available during the short intervals of time required for operation. Obviously in this case efficiency of operation can be sacrificed, and consequently power, in order to obtain a low first cost. Referring to Maxwell's formula for traction or pull

$$P = \frac{B^2 S}{8\pi 980},$$

the pull P is proportional to the square of the armature air-gap flux density B, consequently the total flux required will be less the greater the gap density. A high core flux density and pole face density gives a small core section and consequently a small and cheap magnet. The limit to the decrease in size is the allowable temperature limit of the winding.

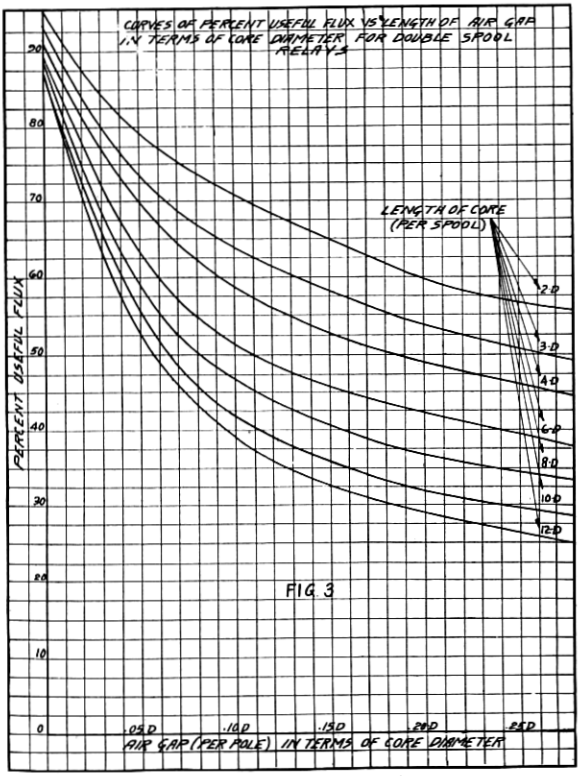

Fig. 3—Curves of Percentage Useful Flux vs. Length of Air Gap in Terms of Core Diameter for Double Spool Relays

Of course, there is a limit to the sacrifice of efficiency to obtain a low first cost. If the reasoning in the preceding paragraph is applied to a 5,000 gram electromagnet, the results will show three to four per cent of the total ampere turns required to saturate the core while on a relay which controls five grams the same assumptions show over 50 per cent of the total ampere-turns required to saturate the core. Where small forces such as five grams are involved, we are almost invariably concerned in maintaining a high efficiency whereas in designs for the heavier forces a few additional ampere-turns required in the core are relatively unimportant.

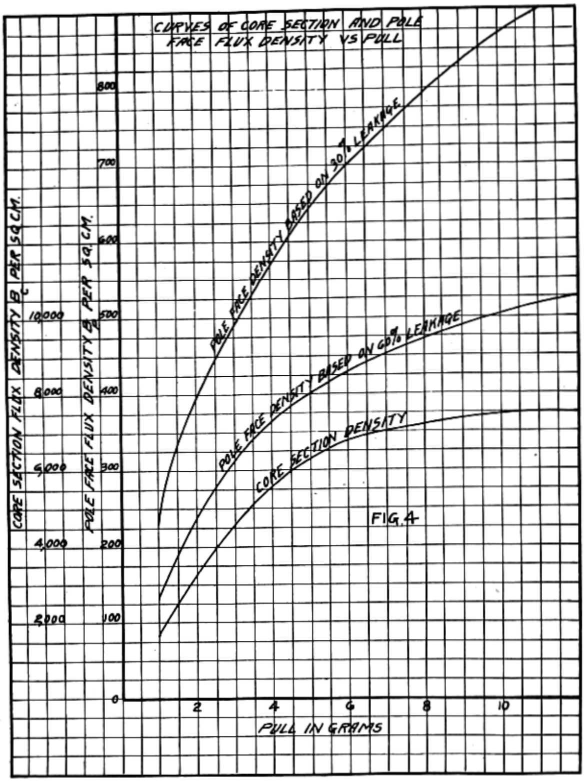

Fig. 4—Curves of Core Section and Pole Face Flux Density vs. Pull

The work done by an electromagnet is $W = 980\ F\ L$ ergs where F is expressed in grams and L in centimeters. The energy in ergs required to magnetize the core is $W' = \frac{\phi NI}{20}$ where NI represents the ampere-turns required to force the flux ϕ through the core. The ratio of the core energy and the useful work may be taken as a criterion of the efficiency of the core design. Applying this reasoning to various designs it is found that the most efficient core design is obtained by choosing a core flux density at the maximum permeability of the core iron. If this reasoning is applied to a 5,000 gram relay a saving of approximately five per cent core energy results over working at a high density but the core section is increased in the ratio of six to one. Obviously the small improvement in efficiency results in an unreasonable increase in size and consequently first cost and is seldom if ever warranted by the requirements. Applying the same reasoning, however, to a five gram relay we obtain a reduction in core energy of approximately 20 per cent and although the core section has greatly increased this increase has practically no influence on the size or first cost of the magnet. Of course, a further consideration is mechanical strength as where light loads are encountered the core section, needed magnetically, may be entirely too small to

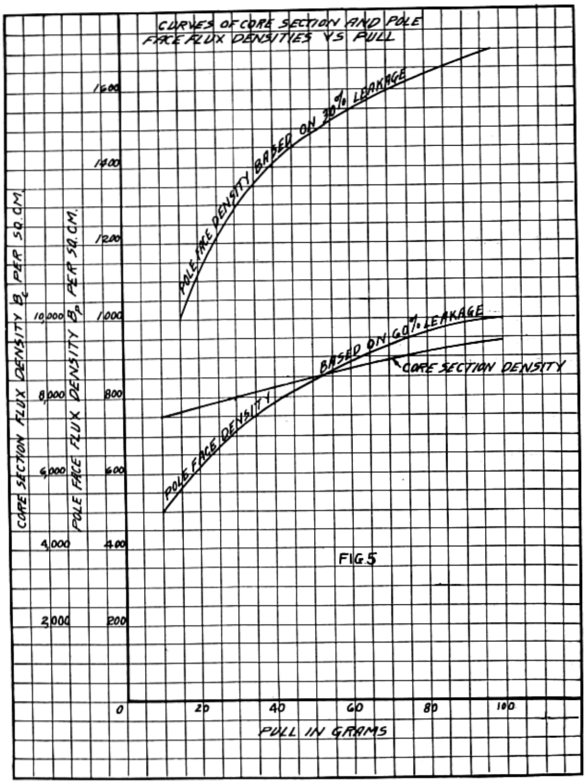

Fig. 5—Curves of Core Section and Pole Face Flux Density vs. Pull

give the requisite mechanical strength for winding or mounting. It may, therefore, be necessary to use a very low flux density in these instances in the core design.

The best flux density and area for the pole face as regards electromechanical efficiency is obtained by making the air-gap reluctance equal to the reluctance of the remainder of the magnetic circuit. Here again it is found that practical considerations must be carefully weighed, otherwise an unreasonable design results. If, for instance, the pole face density on a 5 gram relay is taken equal to the customary core density, a very small pole face area results. To make the air-gap reluctance, then, equal to the reluctance of the remainder of the magnetic circuit, it is found that an air-gap of possibly .001″ or less results. Such a small armature movement, of course, is gener-

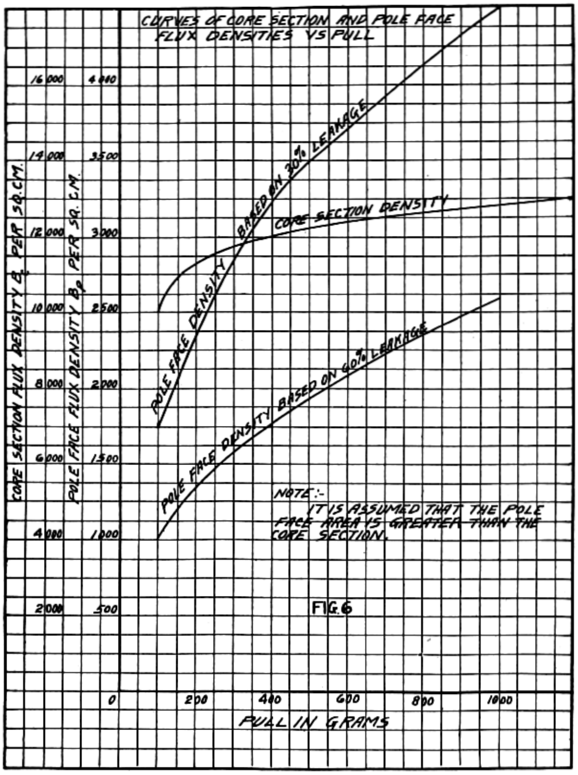

Fig. 6—Curves of Core Section and Pole Face Flux Density vs. Pull. These Curves Assume That the Pole Face Area is Greater than the Core Section

ally of no practical value, and consequently, very low pole face densities are generally chosen.

As a result of the above considerations as well as the experience gained in designing a great number and variety of relays and electromagnets, the curves in Figs. 4, 5, 6 and 7 have been drawn which show reasonable assumptions that may be made in working out new designs. These curves are to be employed, of course, with due consideration of the particular requirements in each case.

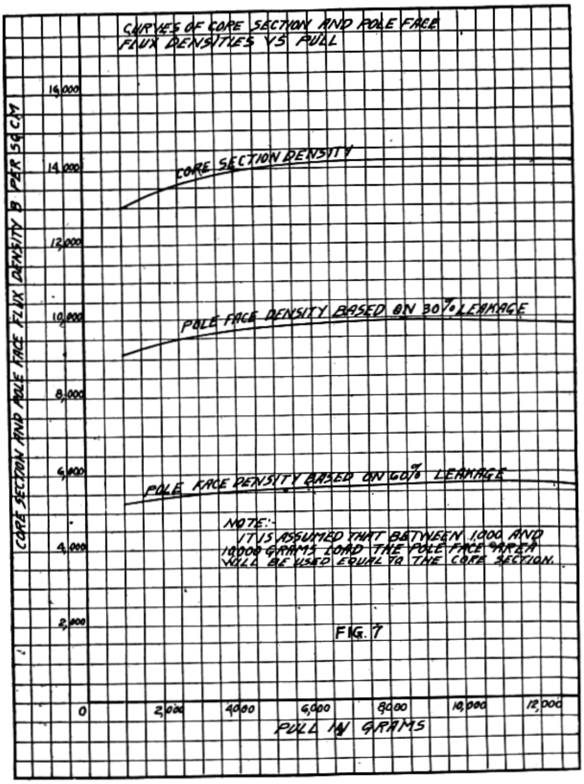

Fig. 7—Curves of Core Section and Pole Face Flux Density vs. Pull. These Curves Assume That Between Loads of 1,000 and 10,000 Grams the Pole Face Area Will be Used Equal to the Core Section

From the above discussion it is evident that magnetic irons which are capable of high flux densities are particularly desirable for the heavier magnets. The high densities permit of a small core section and consequently a small and low cost magnet. The magnets which control loads of a few grams, however, should be constructed of magnetic materials which have a high permeability and a low coercive force, but not necessarily capable of working at high densities. A relatively high permeability reduces the energy required to saturate the core although due to the reluctance of the air-gaps there is obviously a limit beyond which no practical gain results due to increased permeabilities. The most important single requirement of a magnetic material for relays controlling light loads, is a low coercive force. A low coercive force reflects the ability of the magnetic parts to return to practically the same state of magnetization after repeated applications of magnetomotive forces. The effect of residual magnetism, if large, may cause sticking or holding forces of the same order of magnitude as the load requirements. Vacuum annealed silicon steels of comparatively high silicon content and certain nickel steel alloys which have low coercive forces are of great value for electromagnets which must control efficiently light loads of the order of one to fifty grams.

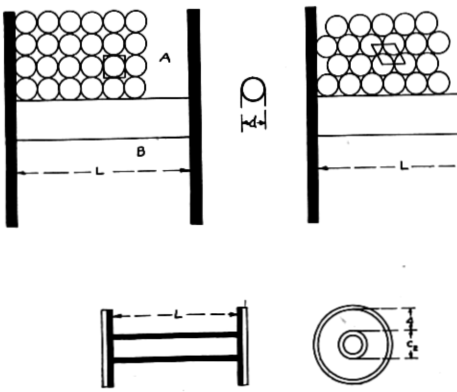

Fig. 8

Winding Formulae

Before discussing the economics of the winding dimensions it is necessary to develop and carefully consider the winding formulae and the factors which determine the temperature characteristics.

Fig. 8 shows the one-half cylindrical section of a spool. Since a given wire occupies a similar space in both A and B we need only to consider winding space A. If d in Fig. No. 8 represents the diameter of the wire over the insulation, it is evident that each wire may occupy one of two positions with respect to adjacent wires. In the uniform layup each wire occupies an area d^2, and with the complete intermeshing of layers one wire occupies an area .866 d^2. In actual winding practice a combination of the two layups is obtained which gives .90 d^2 square inches as the space occupied by one wire. The area .90 d^2 may be taken as indicating perfect winding so that if the total winding space or area is represented by A and the total turns by N, we have under the best conditions

$$\frac{A}{N} = .90\,d^2.$$

The comparative merit or efficiency of any other winding may therefore be expressed as

$$\frac{.90\,d^2 \times 100}{\frac{A}{N}} = \text{per cent efficiency.}$$

As each size of wire and insulation winds with a somewhat different efficiency, the variation in the value A/N is generally determined experimentally for each gauge of wire. Thus

$$\frac{A}{N} = K = C_1\,d^2. \tag{1}$$

The constant C_1 is often designated as a space factor constant and may include the insulating or interleaving paper used throughout the winding. The following are representative values of K for enamel and silk insulated wire of Western Electric Company manufacture.

Values of K

B. & S. Gauge	Enamel Insulated Wire	Silk Insulated Wire
21	.000894	.000936
22	.000718	.000755
23	.000577	.000614
24	.000431	.000477
25	.000437	.0003825
26	.000280	.0003140
27	.000225	.0002615
28	.000183	.0002170
29	.000147	.000180
30	.000120	.0001510
31	.000096	.0001261
32	.0000781	.0001069
33	.0000628	.0000866
34	.0000516	.0000815
35	.0000410	.0000678
36	.0000338	.0000577
37	.0000269	.0000500
38	.0000222	.0000428

Referring to Fig. 8 the space or area available for winding is

$$A = L\Delta. \tag{2}$$

From equations 1 and 2 the total turns possible are

$$N = \frac{A}{K} = \frac{L\Delta}{K} \tag{3}$$

The total resistance of the winding is the product of the resistance of the mean turn R_m and the total turns N,

$$R_t = R_m N.$$

The length of the mean turn for a round core, Fig. 8, is

$$2\pi\left(\frac{C_2}{2} + \frac{\Delta}{2}\right) = \pi(C_2 + \Delta),$$

and if r is the resistance per unit length we have

$$R_m = \pi(C_2 + \Delta)r,$$

whence the total resistance is

$$R_t = \pi(C_2 + \Delta)rN;$$

or substituting the value of N from equation 3,

$$R_t = \frac{\pi(C_2 + \Delta)r\Delta L}{K}. \tag{4}$$

For a core of rectangular cross section equation 3 holds for the total number of turns and it will be found that the equation for total resistance is

$$R_t = \frac{\pi r L\Delta}{K}\left(\frac{p}{\pi} + \Delta\right), \tag{5}$$

where p represents the periphery of the core in inches.

TEMPERATURE CHARACTERISTICS

The critical circuit conditions with respect to the relay winding specify either constant wattage, constant voltage or constant current. The constant voltage circuit is one in which a change in resistance of the relay winding materially affects the current flow. The constant current circuit is one in which a change in resistance of the relay winding does not materially affect the current flow. An approximate constant wattage condition is one in which a resistance such as a line in series with the relay is equal to the resistance of the relay and where the resistance external to the relay winding does not change appreciably with temperature variations.

The temperature formulae for the constant wattage condition are developed as follows:

Let Q be the quantity of heat in calories supplied to the winding per second, and $Q\,dt$ be the amount supplied in a small increment of time. Let S be the product of the specific heat and weight of the total wire on the spool expressed in calories. Let T be the temperature difference between the winding and the surrounding air. $S\,d\,T$ is then the amount of heat used in raising the temperature of the wire by the amount $d\,T$. Let ρ be the average dissipating constant throughout the temperature range. It depends upon the radiating surface of the winding, metal conducting parts of the structure and external convection of heat by the air. Given the constant ρ, $\rho\,T\,dt$ represents the calories dissipated during the interval dt.

The total heat supplied during the time dt is partially used in raising the temperature of the wire, and partially dissipated, consequently

$$Qdt = SdT + \rho Tdt. \tag{6}$$

If heat is continuously supplied the winding in the form of electrical energy, the rate of dissipation ultimately equals the rate of supply. This is true for temperatures that do not fuse the wire or permanently alter its resistance characteristic. Ultimately

$$SdT = 0$$

and

$$Qdt = \rho T_m dt.$$

If the final temperature reached is designated as T_m then

$$Q = \rho T_m \tag{7}$$

and from equations 6 and 7

$$\rho T_m dt = SdT + \rho Tdt,$$

$$-\frac{\rho}{S}dt = -\frac{dT}{T_m - T}$$

and integrating gives

$$-\frac{\rho}{S}t = \log(T_m - T) + C.$$

Observe that when $t=o$ the value of T is also zero and $C=-\log T_m$. Hence

$$T=T_m\left(1-\epsilon^{-\frac{\rho}{S}t}\right) \tag{8}$$

Equation 8 shows that the transient relation between temperature rise T and time is exponential and ultimately the temperature rise is $T=T_m$.

The final temperature T_m reached by the winding may be determined by writing equation 7 in the form

$$\rho T_m=\frac{EI}{4.186} \tag{21}$$

where $E\ I$ represents the constant wattage applied to the winding and 4.186 is the Joule equivalent. If the room temperature is T_r and the ultimate temperature rise T_m, it is evident that the final temperature of the winding is

$$T_f=T_m+T_r,$$

$$T_f=\frac{EI}{4.186\rho}+T_r.$$

By introducing a new constant K_1 which represents the ability of the structure to dissipate heat and also includes the factor $\frac{1}{4.186}$, we have [2]

$$T_f=\frac{EIK_1}{A_1}+T_r, \tag{9}$$

in which A_1 is the area of the winding but does not include the ends.

The value of K_1 can be readily determined by obtaining an experimental curve between $E\ I$ and T_m. This is obtained by gradually increasing $E\ I$ but holding the wattage constant for each value long enough for the final temperature rise to take place. The value of T_m is calculated by observing the change in resistance of the winding.

The constant current and constant voltage characteristics are determined in a similar manner with the important exception that the quantity of heat Q supplied per second is not constant but varies in accordance with the change in resistance with temperature. Thus for constant current conditions $4.186\ Q\ dt=I^2\ R\ dt$ and for constant voltage conditions $4.186\ Q\ dt=\frac{E^2}{R}\ dt$, where $R=\frac{R_0(234.5+T)}{234.5}$ for centigrade degrees and R_0 is taken at 0° C.

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[2] For single spool relays $K_1=50$ to 60, and for double spool relays $K_1=35$ to 50.

The steps by which the solution fitting these conditions are obtained will not be given but the results, stated in practical units, are included to bring out certain important facts relating to winding design. The final temperatures are

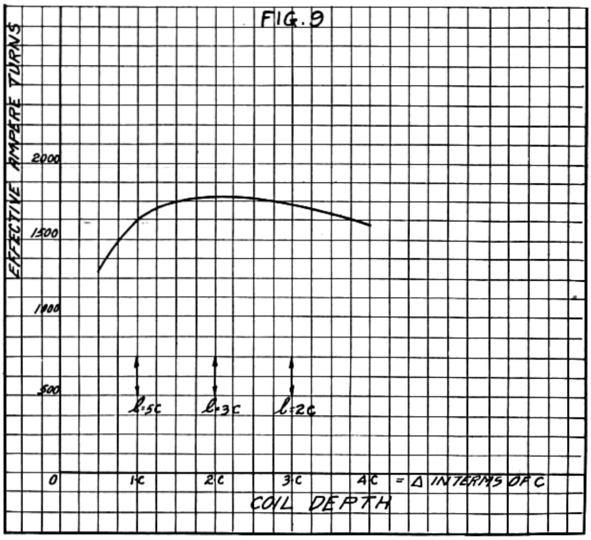

Fig. 9—Relation Between Coil Depth in Terms of Core Diameter and Effective Operating Ampere Turns

$$\text{Constant Wattage, } T_f = \frac{K_1EI}{A_1} + 20°; \tag{10}$$

$$\text{Constant Current, } T_f = \frac{5090A_1 + 234.5I^2R_{20}K_1}{254.5A_1 - I^2R_{20}K_1} \tag{11}$$

$$\text{Constant Voltage, } T_f = -107 + \sqrt{16000 + \frac{254.5K_1E^2}{A_1R_{20}}} \tag{12}$$

The transient temperatures of constant wattage, voltage and current are all of the exponential form $T = T_m\,(1 - \epsilon^{-ct})$, while the cooling of the winding after current is stopped is of the form $T = T_m\,\epsilon^{-ct}$. In these equations c is the constant pertaining to the particular condition considered.

An important observation in connection with these temperature characteristics is the great difference in temperature rise in the three cases with *like initial conditions* of energy input. Thus, it is important to note that an electromagnet which is correctly designed and worked to its temperature limit in a constant voltage circuit, would overheat in a constant wattage or constant current circuit. A relay properly designed to work at a safe temperature under a constant current condition, would be unnecessarily large and expensive in a constant voltage or constant wattage circuit. It is, therefore, evident that exact rules can not be given for the correct proportioning of spool and winding dimensions from a purely design standpoint without consideration of the circuit in which the electromagnet is to operate. Some general design features, however, can be indicated which will enable preliminary assumptions to be made that can be refined as the design is worked out for its particular operating conditions.

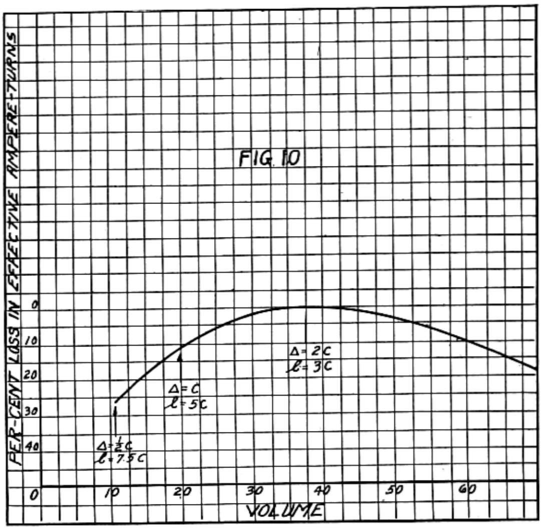

Fig. 10—Relation Between Copper Volume and Percentage Loss in Effective Ampere Terms

Spool Dimensions

Certain important facts regarding spool dimensions are indicated in Fig. 11. The spool dimensions for the winding may be investigated by assuming that a definite radiating surface must be used to dissipate the heat, and then determine the relative values of winding depth, length, and volume in terms of the core diameter. The volume of wire used in the spool is taken as a measure of the first cost and a variation in the length of the coil is reflected in the leakage flux which in turn may be taken as a measure of the effective ampere turns. The determination of the leakage flux involves reasonable assumptions from experience of the armature air-gap in terms of the core diameter.

If the electromagnet is to be operated on a definite voltage the assumption of a definite radiating surface to dissipate a certain input wattage will fix the resistance of the coil. Copper windings of electromagnets in telephone systems are generally wound with wire which varies from No. 20 B. & S. to No. 39 B. & S. gauge. The resistance generally varies throughout a range of ½ ohm to 2,000 ohms. Various gauges of wire wind with different efficiencies due to variations in the space factor but a number of different gauges may be assumed and the calculations carried out which give the relation between the winding depth and the effective ampere-turns. With a constant radiating surface a variation in the winding depth causes a variation in the length which, of course, is reflected in the leakage flux. The results of a number of calculations on various windings are shown in Fig. 9. In Fig. 10 is shown the relation between the volume of wire on the spool and the per cent loss in efficiency due to a variation in the depth of winding which, with a constant [3] radiating area, causes

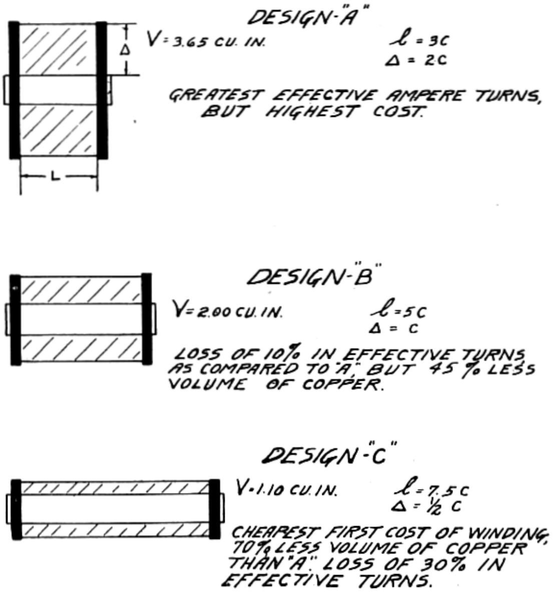

Fig. 11

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[3] The radiating area is taken as the surface only of the coil and the ability to dissipate through the ends and otherwise is reflected by the heating constant K_1.

a corresponding change in the length of the coil. Fig. 11 shows the relative dimensions of three designs of spools taken from Figs. 9 and 10.

Some very interesting information can be obtained from Fig. 11 in regard to the relation between the volume of wire, as reflecting the first cost, and the ampere turn operating efficiency. Design "A" contains a volume of copper of 3.65 cubic inches, while in design "B" the volume of copper has been reduced to 2.00 cubic inches although the loss in effective ampere-turns is only 10 per cent. In design "C" the volume has been reduced to 1.10 cubic inches with a loss in efficiency of 30 per cent.

Obviously the design "C" is the cheapest in first cost because of the small copper volume and will also give the lowest annual charge where the time of operation is very short and the charge for power relatively low. Where the magnet is required to operate very often and the price of power is high the design "A" will prove the most economical. Design "B" may be considered as intermediate between designs "A" and "C".

In the above considerations of spool dimensions the examples given should not be taken as an accurate generalization but simply as a method which, with a given set of requirements, should enable reasonable first approximations to be made. Thus, if annual power charges are controlling, a relatively short and deep spool will give the best results, although there may be exceptions where for instance, the operating current is reduced to a holding value and where the leakage is relatively small due to the fact that the armature is operated. In such a case and unless operating efficiency is also of prime importance the design "A" would be more expensive than necessary in first cost. Other cases often arise where the input wattage is very small but the operating requirements are very exacting so that the most efficient winding is required and the first cost is relatively unimportant. In this case a larger volume than "A" can be used to advantage. These examples may be used as a guide therefore, in determining spool dimensions which are later refined as the design is completely worked out. The illustrations of designs given in the latter part of this paper show how accurately certain final design dimensions can be worked out to give the minimum annual charge.

DISCUSSION OF DESIGNS USED EXTENSIVELY IN THE TELEPHONE PLANT

To any one familiar with telephone systems it is obvious that it is impracticable to design all the relays required at maximum efficiency and economy for each particular condition that arises. Such a procedure would involve endless equipment changes as well as the large and unnecessary manufacturing expense of making an excessive number of types of relays. Much of the relay engineering work of the past few years has therefore been directed toward the standardization of relay designs which would be flexible, reliable and economical as a whole in the telephone plant rather than the most efficient in all respects for any specific condition. The flat or punched type relay manufactured by the Western Electric Company represents largely the result of this effort.

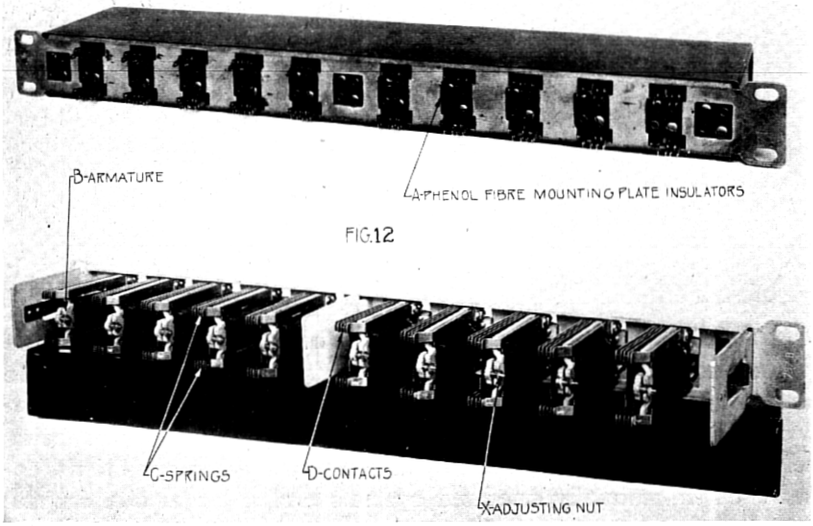

Fig. 12

The flat relay is essentially a punch press product manufactured yearly in large quantities and in about 3,000 varieties of windings and switching or contacting arrangements. The punch press method produces parts which are exact duplicates and therefore interchangeable which is particularly advantageous both for assembly and replacements or repairs. All the springs as well as the core and armature are punched and formed in bending fixtures to the required shapes. The mounting plates are also punched and designed to permit of uniform and economical mounting of the relays.

A number of these relays are shown on a punched mounting plate in Fig. 12. Referring to the figure it will be seen that the relays are insulated from the mounting plate by phenol fibre insulators "A," which are securely fastened to the mounting plate by means of metal eyelets. The armature "B" is hinged at the rear by the use of a thin, steel reed, securely riveted to the armature. The switching arrangements which the armature controls are in the form of nickel silver springs "C" with the contacts "D", at the front and in plain view.

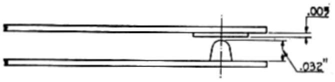

Fig. 13

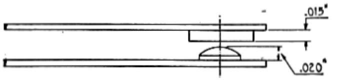

Fig. 14

The springs and contacts are mounted vertically which is particularly effective in keeping the contacts clean. The contact points are made from platinum or a recognized equivalent, and are designed in the form of points and discs to facilitate alignment and adjustment. Two designs of contacts have been standardized; one size being used for the customary electric currents and wear conditions encountered in manually operated systems and a larger size for the somewhat more severe conditions of wear frequently encountered in automatic systems. All contacts are electro-welded on their respective spring supports and the two sizes are shown in Fig. 13 and Fig. 14, respectively.

The springs and their associated contacts are designed in twenty-six switching arrangements as shown in Fig. 1. A single relay may be provided with one of these switching arrangements or any one of these twenty-six arrangements may be paired with any other arrangement. Thus on a single relay there may be chosen any one of 377 switching or contacting combinations. The 377 spring combinations provide a great flexibility in circuit design and permit of uniform and efficient equipment layouts.

In manufacturing the relays the spring assemblies are clamped together under high compression before tightening the screws which hold them together. This insures that the springs retain their position and adjustment throughout a long period of time. The arrangement of the springs is such that definite stops or supports are provided for each spring either on the front spool head or on the armature. In tensioning or adjusting the relay springs against their supports, sufficient tension is set up in the springs to insure a pressure of at least 15 grams between all contacts at the time of closure.

The amount of current and power required to operate each relay is dependent upon the tension and number of springs that must be moved and the distance through which this movement takes place. Relays or electromagnets operate most efficiently with the armature air-gaps set at the minimum required for the satisfactory opening and closing of the contacts. Consequently a method has been carefully worked out for these relays in which the armature travel is set in accordance with the requirements of the particular spring combination by the adjustment of the friction lock nut "X" shown in Fig. 12. This setting of the armature insures a normal separation of contacts of approximately .010 inch and at least .005 inch "follow" after closure of the contacts. The "follow" allows for a certain amount of contact wear as well as insuring a slight wiping action which gives a certainty of contact closure. The electrical operating current requirements are figured and specified on the basis of obtaining 20 grams pressure between all contacts; this margin being allowed so that no undue hardship will be experienced in maintaining the minimum requirement of 15 grams.

The insulating materials used throughout have been carefully studied and the best materials known to the present day art have been used. Thus the wire used in the winding is insulated with a high grade enamel and the insulating papers on the core are practically inert from an electrolytic corrosion standpoint. The coils are covered with a serving of cotton, treated with unbleached shellac which acts as a seal against moisture and protects the winding from abrasion. The phenol fibre used on the spool heads and spring insulators is much superior to hard rubber in regard to its ability to withstand a wide temperature range without appreciable expansion or contraction.

For this reason it is permissible to work these relays at higher temperatures without danger of fire hazard or deterioration of the insulation than relays insulated with hard rubber parts. These higher temperature limits permit a wider usefulness of the relays in circuits as well as economy in construction as the size of the coil often depends on the necessary area for radiation and this area is fixed by the permissible temperature range.

Where the relays are to remain operated a considerable length of time throughout the day the annual power charges become important and the design of the winding and in some cases the size of the spool must be altered to give the minimum annual charge. The group of curves in Fig. 15 show how nearly correct these relays have been designed for conditions where the operating ampere-turns are 260 and the relays remain operated from 60 to 600 minutes per day.

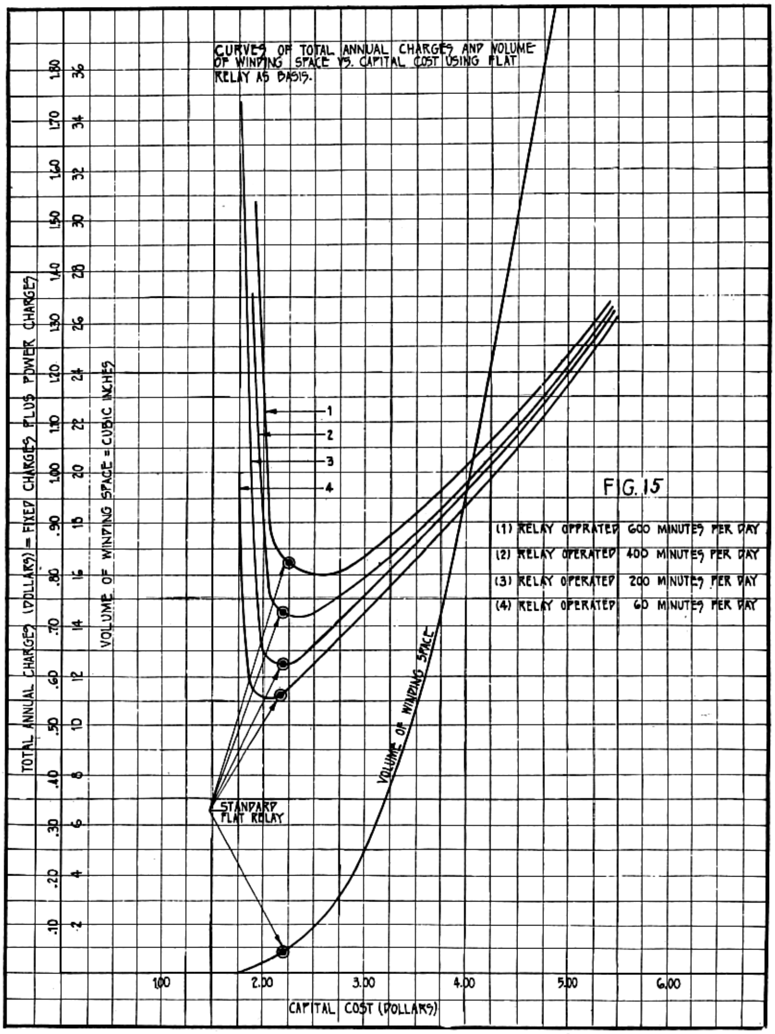

Fig. 15

The capital cost and annual charge figures should be taken as relative only as the correct values will vary with manufacturing conditions and with the cost of power for different localities.

Other designs of relays used extensively in the telephone plant are the relays that control the supervision of a telephone connection and the alternating current relays which operate on ringing currents of 16 to 20 cycles frequency.

Relays which are used for supervisory purposes and alternating current relays are generally constructed of silicon steel instead of the customary Norway or magnetic iron. The silicon steel is very satisfactory for these relays because of its comparatively high permeability, low coercive force and small hysteresis. The high permeability is advantageous for relays that are required to operate on a very small energy input and the low coercive force is very effective for obtaining a quick and positive release of the relay armature, particularly where a leak current exists due to faulty line insulation. A great improvement in many of these relays can be obtained by the use of certain nickel-iron alloys which have been recently developed and are known as "Permalloy."

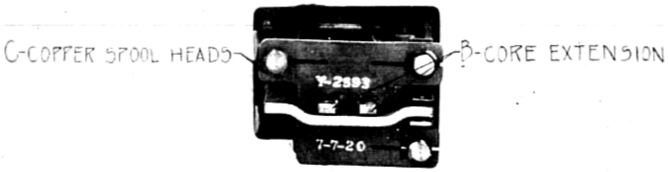

Fig. 16

A relay for use on ringing currents is shown in Fig. 16. The armature "A" of this relay is attracted to the bifurcated extensions of the core "B." One of these core extensions is completely surrounded by a part of the copper spool head "C." This arrangement is known as pole "shading" or phase splitting and is used to produce a substantially steady pull on the armature when the relay is energized by single phase alternating current.

Referring to Fig. 17 the theory of operation is shown by considering the vector diagram in connection with the schematic drawing of the relay core and armature. When an alternating current is applied to the winding we can assume that an alternating flux $2\ \phi_m$ is generated in the core. This flux divides into two approximately equal parts in the two bifurcated extensions of the core. If these two fluxes can be displaced in time phase it is evident that the armature will be attracted by one of the bifurcated extensions of the core, while the flux, and consequently the attraction of the other, is passing through zero. This may be explained by the vector diagram in which E_2 represents the induced voltage in the short circuited copper ring due to the alternating flux ϕ_m. The current in the copper ring I_2 lags behind the voltage E_2 as shown and the flux due to this current is ϕ_r. This flux ϕ_r has a magnetic path through the bifurcated pole pieces and armature as shown by the arrows. Following out the arrows it will be seen that this flux adds to the flux ϕ_m in the upper part and subtracts in the lower part of the two core extensions.

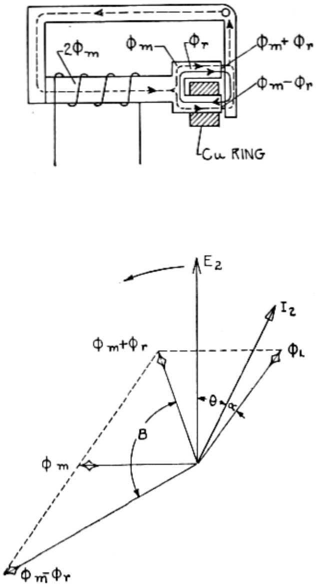

Fig. 17

The vector addition and subtraction of these two fluxes results in two vectors $\phi_m+\phi_r$ and $\phi_m-\phi_r$, each of which represents a flux that crosses an air-gap to attract the armature. These two fluxes differ in time phase as represented by the angle "B" so that a substantially constant attraction results on the armature. The operation of the relay under these conditions is very much the same as that of a direct current relay as no vibration or chatter of the armature or contacts occurs. The minimum effective alternating current ampere-turns required for operation are 70 to 100 ampere-turns.

Such a relay, of course, operates on direct current as well as on alternating current and in fact the direct current supervisory relays are quite similar to these relays in mechanical design.

Fig. 18 shows the design features for the supervisory and ringing frequency relays. In this figure the winding has been omitted so as to show clearly the unusually small core. This construction is especially efficient in circuits where the relay receives at times a very small amount of energy for operation and must also release reliably against a leak current immediately after operation by a comparatively large amount of energy. The small core saturates magnetically on a relatively small current or energy so that excessive energy does not store up additional magnetism which would retard or prevent the release of the relay.

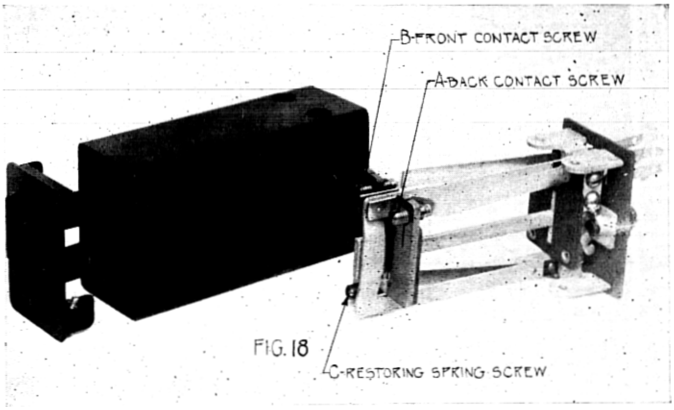

Fig. 18

Referring further to Fig. 18 the micrometer screws "A" and "B" are used to adjust the back and front contacts respectively, and to fix both the unoperated and operated positions of the armature. The screw "C" is used to control an armature restoring spring which is in the form of a flat spring riveted to the armature. These relays are generally provided with individual covers which are effective in preventing cross talk of telephone voice frequencies when used as supervisory relays in telephone switchboards.